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The effect of sleep restriction on neurobehavioural functioning in normally developing children and adolescents: Insights from the attention behaviour and sleep laboratory

L'effet de la restriction de sommeil sur les fonctions neurocomportementales des enfants et des adolescents qui développe normalement : perspectives de la laboratoire de l'attention, du comportement et du sommeil

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ABSTRACT

In the current paper, we first introduce the research themes of the attention, behaviour and sleep (ABS) laboratory, namely, sleep and ADHD, sleep and obesity, and sleep and academic performance. We then focus in on the topic to be reviewed in the current paper – the association between sleep restriction and neurobehavioral functioning (NBF) in typically developing children. We review the research thus far conducted by the ABS lab specific to this topic and posit the unique methodological contributions of the ABS lab (e.g. home-based assessment of sleep architecture and patterns, extensive phenotyping, etc.) in terms of advancing this research area. In the second section of the paper, we review 13 studies investigating the causal association between experimental sleep restriction and NBF in normally developing pediatric populations. Eight of the 13 studies found that sleep restriction causes impairments in neurobehavioural functioning. However, given the inconsistency in outcome measures, experimental protocols and statistical power, the studies reviewed herein are difficult to interpret. Strategies used by the ABS including implementing home assessments of sleep, restricting sleep relative to the participants' typical sleep schedules, blinding raters who assess NBF, and using valid and reliable NBF assessments are an attempt to address the gaps in this research area and clarify the causal relationship between sleep restriction and NBF in typically developing children and adolescents.

Mots clés :
Restriction de sommeil
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Attention
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RÉSUMÉ

Dans cet article, nous introduisons d'abord les thématiques de recherche du laboratoire d'attention, de comportement et de sommeil (LACS), notamment les liens entre le sommeil et le TDAH, entre le sommeil et l'obésité, ainsi qu'entre le sommeil et la performance scolaire. Ensuite, nous discutons de l'association entre le manque de sommeil et les fonctions neurocomportementales (FNC) parmi les enfants se développant normalement. Nous présentons une revue de la recherche effectuée jusqu'à maintenant par notre laboratoire sur ce sujet ainsi que la contribution méthodologique unique (ex. l'évaluation du sommeil à domicile, le phénotypage élargi, etc.) vers une meilleure compréhension dans ce domaine de recherche. Dans la deuxième section de l'article, nous présentons les résultats de 13 études examinant l'association causale entre le manque de sommeil expérimental et les FNC parmi les enfants au

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développement normal. Huit études parmi les 13 présentées démontrent que la restriction de sommeil entraîne une diminution importante des FNC. Par contre, l'interprétation globale de ces études est difficile en raison de différences sur la façon de mesurer les résultats, sur les protocoles de recherche et sur la puissance statistique entre les études. Les stratégies utilisées par le LACS, dont l'évaluation du sommeil à domicile, la restriction de sommeil relatif aux horaires habituels de sommeil des participants, l'évaluation des FNC de façon aveugle, et l'utilisation de mesures de FNC valides et fiables forment dans leur ensemble une tentative importante de combler les manques présents dans ce domaine de recherche et d'éclaircir l'association causale entre la restriction de sommeil et les FNC parmi les enfants et les adolescents au développement normal.

The first goal of this paper is to introduce the research objectives and themes of the attention, behaviour and sleep (ABS) laboratory. We will then present the focus of this paper, namely, sleep restriction and neurobehavioral functioning (NBF) in normally developing pediatric populations. We will discuss the research thus far conducted by the ABS lab specific to this theme and posit the unique contributions of the ABS lab in terms of advancing this area of research. Next, we will review other studies investigating sleep restriction and NBF. We will conclude by integrating the findings of the reviewed studies and evaluating how the contribution of the ABS lab may be useful in advancing this field of research.

1. The attention behaviour and sleep laboratory

Increasing evidence indicates that sleep has beneficial effects on learning and memory [1], emotional regulation [2], health [3], and academic achievement [4]. Conversely, fatigue and insufficient sleep negatively affect these life domains, each of which must function well to ensure optimal development. However, a considerable proportion of children and adolescents do not achieve adequate sleep, in terms of either quantity or quality [5,6]. Clinical studies [7] strongly suggest that poor sleep is implicated in the development and persistence of prevalent childhood disorders affecting youth mental (e.g., attention deficit/hyperactivity disorder [ADHD]) and physical (e.g., obesity) health. Appropriate use of sleep knowledge by educators and clinicians may significantly improve youth performance and health [8]. However, the mechanisms that underlie the associations mentioned above remain unclear and translation of available knowledge for the benefit of youth is currently lacking. Uncovering the mechanisms isimportant because it is likely that a key means of using existing information to improve the health and success of children is being overlooked. Thus, the objectives of the ABS lab research program led by Dr. Reut Gruber are to fill these knowledge gaps, by examining the mechanisms underlying the associations between sleep, and cognition and health in youth, and by developing a means whereby such knowledge can be used to improve the health and learning capacity of young persons. The *rationale* of this research program is that a better understanding of how sleep affects mental and physical health will allow identifying ways of modulating such interactions, forming the basis for developing innovative prevention and intervention programs in three domains:

- sleep and ADHD (theme 1);
- obesity (theme 2);
- sleep and academic performance (theme 3).

This research program is situated within the integrative field of developmental cognitive neuroscience, pediatrics, and psychiatry, and within the expanding field of knowledge translation.

1.1. Theme 1 – Sleep and ADHD

ADHD, one of the most prevalent child psychiatric conditions, is characterized by core symptoms of chronic and significant inattention and/or impulsivity/hyperactivity [9]. ADHD is estimated to occur in approximately 5% of school-aged children, and clinical manifestations frequently continue into adolescence and adulthood [10]. If left untreated, individuals with ADHD remain impaired in crucial functional domains (academic, occupational, and social). In clinical practice, sleep problems are reported in up to 55% of children and adolescents with ADHD [11]. However, the association between ADHD and sleep disturbance remains poorly understood. The ABS lab conducted a series of studies [12–15] in order to characterize the sleep of children with ADHD, to identify causes of sleep differences in children with ADHD, and to measure their impact on the daytime functioning of children with ADHD. The lab seeks to use this knowledge to develop strategies to prevent or treat daytime problems caused or exacerbated by sleep deficiencies.

1.2. Theme 2 – Sleep and obesity

Childhood obesity continues to rise both in Canada and worldwide [16], despite medical and behavioral interventions seeking to prevent weight gain and the implementation of various significant public health initiatives. Recent research has found evidence of a link between shorter sleep duration and overweight and obesity in children and youth [3]. Shorter sleep duration results in hormonal changes [17] comparable to those associated with increased risks of obesity [18], diabetes [19], and hypertension [20]. Hence, sleep curtailment may be an important, modifiable risk factor for obesity. Evidence is growing that obesity not only features elevated caloric intake and poor weight management, but is also linked to adverse neurocognitive outcomes, specifically poorer executive functions [21]. Consistent with this notion, there is evidence that obese children are more impulsive than are normal-weight children and have less cognitive control. The ABS lab studies the overlap that may exist among cognitive processes pertaining to decision-making, self-control, and impulsivity affected by sleep disruption and those associated with obesity [22].:

1.3. Theme 3 – Sleep and academic performance

The third theme of the ABS lab is related to sleep and academic performance. Academic success plays an important role in improving future lifetime opportunities. Considerable research data support a relationship between sleep and academic success [4]. Although a myriad of factors relevant to academic achievement have been identified, the role played by sleep in this process, in particular the negative impact of insufficient sleep on NBF, has been largely ignored. Information on the connection between sleep and academic achievement has been gathered in multiple

studies [23]. In parallel, knowledge has accumulated on the role played by sleep in basic neurobehavioral processes associated with performance at school [24]. However, despite the mutual relevance of such studies, work on these topics has proceeded independently, and a mechanistic understanding of the observed association between sleep and academic achievement has been lacking.

Dr. Gruber published a conceptual paper [4] presenting empirical evidence for an association between sleep and academic performance in children and adolescents, and suggesting the neurobehavioral mechanisms that might underlie such associations. Specifically, Dr. Gruber suggested that:

- sleep is closely related to the optimal use of executive functions, is essential for completion of the learning and memory processes, and affects IQ;
- these key cognitive processes have been repeatedly and widely shown to be predictive of, associated with, and essential for, academic success in both children and adolescents;
- these, then, are possible neurobehavioral mechanisms explaining the observed association between sleep and academic performance [22].

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2. The association between sleep and neurobehavioral functioning in typically developing children

Sleep restriction has negative effects on NBF [24,25], especially on functions essential to academic success, including attention/response inhibition, memory, verbal creativity, problem solving, and general cognitive abilities. A modest but chronic reduction of just 1 h of sleep per night can have a significant negative impact on cognitive performance [25]. For example, short sleep duration increased the risk of low performance on measures of vigilance 3.1 fold, and increased the risk of lower performance on the Block design subtest of an IQ test (the WISC) 2.4 fold [26]. Cumulative sleep restriction has negative effects on cognitive performance [25,27], with consistent evidence for an inverse relationship between sleep time and school performance. As many as 24% of adolescent students reported that their grades dropped because of sleepiness [28]. A comparison of school performance measures with reported total sleep time found that students who had grades of C, D, or F averaged 25–30 min less sleep per weeknight than did their peers with better grades [29].

A recent narrative review of the literature on the functional consequences of sleep deprivation in healthy pediatric populations concluded that a deficit in sleep quantity or quality can lead to inattention, which can impact school functioning [30,31]. Lufi et al., [32] examined the impact of delaying a high school's start time by 1 hour for 1 week on students' performance on neurocognitive attentional tasks. Results indicated that students slept 55 minutes longer each night and performed better on the attentional tasks as compared to during the delayed school schedule.

The next section describes the research and contributions of the ABS in the context of sleep and NBF.

A series of empirical studies have been conducted to examine the impact of pre-learning sleep deprivation on neurobehavioural functioning of children. First, it was shown that there is significant relationship between sleep fragmentation and NBF in school-aged children [24]. Then, it was found that lower sleep efficiency and shortened sleep compromised NBF, particularly executive functioning, memory, and sustained attention [25]. In a more recent study the role of sleep in cognitive processes has been further investigated by examining the interplay between sleep and IQ [22]. It was found that longer habitual sleep duration in healthy school-aged participants was associated with better performance on measures of perceptual reasoning and overall IQ. In another study [14], it was found that lower sleep spindle frequency was associated with better performance on the perceptual reasoning and working memory WISC-IV scales, but that sleep spindle amplitude, duration and density were not associated with performance on the IQ test. These findings contribute to understanding the neurophysiological mechanisms underlying the relationship between longer sleep duration and better performance on certain subscales of IQ tests.

In addition to generating empirical data on mechanisms potentially underlying the association between sleep and NBF functioning, the ABS lab examined the association between sleep and day-to-day functioning of children in school in order to understand the impact of sleep deficiency on daily functioning of typically developing children. It was found that short sleep duration was associated with teacher-reported inattention and cognitive problems of healthy school-aged children [33]. Although the findings are important, the study was correlative in nature, as is most research in the field and causality could thus not be determined. The next research objective was to investigate whether sleep duration was directly and causally related to on day-to-day functioning in school. The ABS lab conducted the first-ever experimental study evaluating the impact of experimental sleep extension and restriction on day-to-day functioning in school of typically developing children [12]. Using a randomized parallel group design to test the impact of experimental changes in sleep duration (sleep extension: addition of 1 h of sleep relative to baseline habitual sleep duration on weekdays; and sleep restriction: elimination of 1 h of sleep relative to baseline habitual sleep duration on weekdays) on child behavior and performance in school. Results showed that modest changes in sleep duration significantly affected the behavior of typically developing children. Modest sleep extension (i.e. average of 27.36 minutes over five nights) resulted in significant improvement in Conners' Global Index-derived emotional lability and restless-impulsive behavior scores of children in school, whereas modest sleep restriction (i.e. average of 54.04 minutes over five nights) had the opposite effect. The finding that modest changes in sleep can have a significant on daytime behavior emphasizes the importance of providing sleep education to parents, educators, and students featuring data on the critical impact of sleep on daytime function and offering concrete tools to help children obtain a sufficient amount of sleep.

Collectively, the studies conducted by the ABS lab have extended previous research findings by providing empirical evidence for the interplay between sleep and key processes associated with NBF of children at school. Further, the results imply that intervention programs aimed at increasing sleep duration might have detectable positive effects on learning capacity and performance of school-aged children.

To translate these findings into action, the ABS Lab in collaboration with community partners created "sleep for success" (SFS) [34], – a program aimed at changing the sleep habits of school-aged children. SFS is a comprehensive, multi-module program developed to move research findings about the benefits of sleep for academic performance by integrating sleep education into the curricula of elementary schools. The program is composed of five distinct modules addressing the children, their families, the school staff, and decision-makers within school settings, and a training module. Working with community partners, the ABS lab conceived, developed, evaluated and disseminated this program. The impact of SFS on participating students was assessed by evaluating their sleep and daytime functioning at baseline and during the week following implementation of the program. Preliminary results showed that children demonstrated an increased in sleep time following the program as compared to baseline, as measured by actigraphy. Further sleepiness and sleep-onset delay were reduced following implementation compared to baseline.

3. Unique methodological contributions of the ABS lab in understanding the relationship between sleep restriction and NBF

3.1. The experimental approach

Most previous studies examining the association between sleep and daytime functioning in children were correlative, prohibiting inference of cause and effect. The ABS lab developed a home-based experimental paradigm to investigate potential causal relationships between sleep and daytime functioning. It employs actigraphy, a wristwatch-like device designed to measure activity (as a proxy for sleep) in the natural environment of the child, asks participants to manipulate sleep for an extended period of time (i.e. several successive nights) at home, and measures the impact of these changes on daytime parameters. By experimentally extending or restricting sleep, the effects of such changes on cognitive, behavioral, and emotional processes can be determined. This experimental approach represents an important methodological contribution to pediatric sleep.

3.2. Home-based assessment of sleep architecture and patterns

The results of earlier studies on child sleep are of limited ecological validity because of the inevitable "trade-off" between the quantity and quality of objective or physiological data collected and the extent of interference with natural sleep. Often, collection of physiological measures required children to sleep in laboratory settings, thus creating stress, which is known to affect sleep, as well as emotions, behavior, memory and learning. The results of such studies must therefore be interpreted with caution. Also, both the child and the family are seriously inconvenienced. To overcome these methodological barriers, the ABS lab has acquired the equipment and expertise necessary to conduct ambulatory home-based assessment of sleep architecture. These methods allow accurate and reliable data collection in the absence of laboratory stress. The exploration of sleep-dependent mechanisms and associated neurobehavioral outcomes in children and adolescents is thereby rendered feasible and ecologically valid.:

3.3. Comprehensive phenotyping

The selection of neurobehavioral outcome measures that are affected by sleep and that are of most relevance to the daytime functioning of children and youth is an important methodological issue. Such measures must be both sensitive to small changes in NBF, relevant for pediatric populations, and implemented at multiple time points if the impact of sleep changes on daytime functioning, in particular school performance, is to be fully understood. The ABS lab employs specialized measures characterizing cognitive and attention function to identify the impact of sleep on specific neurobehavioral factors including objective and ecologically valid measures of executive functioning, vigilance, arousal, sustained attention, learning, and memory.

When assessing NBF of normally developing children in academic settings, the ABS lab involves raters (i.e. classroom teachers) who are blind to the experimental condition of the students. This eliminates the rater bias that accompanies self-report assessments. Whether assessing neurobehavioral characteristics at the screening phase of a study or assessing consequences of experimental sleep restriction, the ABS lab's research protocols are conducted in a safe, flexible, and convenient manner, with respect for the needs of the children.

3.4. Participatory research

The ABS lab conducts translational participatory research to develop sleep-related intervention programs. Translation of research findings into practice is always desirable, but the translation rate has often been "inefficient and disappointing" [35]. Community-based participatory research is a knowledge transfer approach that differs from traditional research in that the work is collaborative. The participatory research approach allows for the translation of experimental research findings into practical applications in real world settings. It is instrumental in filling the gap between research and practice, as it informs the way in which interventions can incorporate empirical research findings while respecting the practical needs of the community in which the intervention will be implemented.

4. The current review

The goal of this section of the paper is to critically examine evidence regarding the effects of experimentally restricted sleep on the NBF of typically developing children and adolescents.

NBF is defined as behaviors such as difficulties with attention, impulsivity, hyperactivity, performance skill difficulties, and aggression in addition to executive functioning abilities [36]. Partial sleep deprivation is a common occurrence in pediatric populations affecting 25–30% of normally developing children and adolescents [37]. Understanding the impact of sleep restriction on the NBF of normally developing pediatric populations is therefore important as it can inform the development of interventions aimed at improving children's daytime functioning by improving their sleep. We will first review studies in which researchers have experimentally manipulated sleep duration in pediatric populations (under the ages of 18 years old) and investigated its impact on NBF. We will conclude by discussing methodological limitations and potential solutions that the ABS has developed, which can inform future directions in this research field.

5. Methods

We carried out a literature search on the three major medical and neuropsychological databases using Ovid® database platform. Three databases were Medline® (1946 to Dec 23, 2013), Psychinfo® (1967 to December week 3, 2013) and EMBASE® (1967 to December week 3, 2013). The keyword combination used was: (sleep restrict* or sleep depriv*) or (adolesc* or teen* or youth or young or child or pedia*) and (attention) not (clinical or disorder). We reviewed studies that evaluated the impact of experimental sleep restriction on NBF in children and adolescents. Information extracted from experimental studies included details about authors, publication year, participants' demographics (age and sex), design (between-subject or within-subject), sample size, description of sleep restriction protocol, sleep measures and how they were used to assess adherence during protocol, attention-related outcomes, and main findings in terms of effects sizes, statistical tests and P values. We used the Down and Black 27-item criteria [38] was used to assess the quality of experimental studies [38,39]. This criteria evaluates studies on the basis of reporting (9 items), external validity (3 items), bias (7 items), confounding (6 items), and power calculations (1 item). As prescribed previously, a cut off of 15 or more score was applied to selected studies before final review [39].

6. Results

A total of 691 references were retrieved from the three databases. After removing duplicates, 432 abstracts were further

scrutinized by the two reviewers. Inter-reviewer agreement for inclusion was good (Kappa coefficient = 0.65). Final selection included a total of 13 studies [12,13,40–50]. All studies were published in English language. All experimental studies fulfilled the Down and Black criteria recommendations by scoring 15 or higher score (median = 20; interquartile range 18–21). Please refer to Table 1 for a complete list of studies.

7. Sample

The study sample sizes ranged from 6 to 82 (median = 22, interquartile range = 13–55). Overall, the studies included participants aged from 6 to 16 years. The age ranges in seven studies were from 11 to 16 years [40–43,45,48]. Males and females were equally represented in all samples.

8. Design

Most studies [13,40–46,48] employed a within-subjects design in that NBF was compared within the same participants before and after sleep restriction (see Table 1). Several of the within-subjects designs were cross-over designs [40,42,45,47,48] in that participants experienced other conditions in addition to sleep restriction in a counterbalanced order [40–42,45,47,48]. Four of the cross-over studies included sleep restriction and sleep extension conditions [40–42,47], while two had sleep restriction and sleep as usual conditions [45,48]. Four studies [12,46,49,50] employed a between-subjects design in that NBF was compared between groups. In this design, one group underwent the sleep restriction protocol while the other group underwent sleep as usual or a sleep extension protocol.

9. Sleep restriction protocol

There were several protocols used to restrict sleep in the reviewed studies. In general, the design of the sleep restriction protocol was a function of the design of the study (i.e. between-subjects or within-subjects). In the studies that employed a within-subject design, participants were exposed to a baseline period that consisted of sleep as usual (e.g., [41]) or a predefined number of hours of sleep in order to ensure that sleep was stabilized prior to the commencement of the sleep restriction period (e.g., [43]). Following a baseline period, which took place for one night in some studies [43,44,48] and 1 week in other studies [12,13,40–42,45–47], the participants then underwent sleep restriction. For between-subjects design studies, the stabilization period was identical to within-subjects design studies [12,13,46,47] except that two groups underwent the baseline sleep period prior to being assigned to either the sleep restriction group or the alternative group (sleep as usual or sleep extension). The number of nights in which sleep was restricted differed across all studies and designs, comprising of one night [43–46,48], three nights [50], six nights [12,13], or seven nights [40–42,47]. The number of hours by which sleep was restricted was a function of the number of nights that the child was sleep-restricted. For example, sleep was restricted to 4 hours in the studies having only one night of sleep restriction [43–46,48], whereas sleep was restricted 6.5 or 8 hours per night if the sleep restriction protocol took place for one week [40–42,47]. While some protocols restricted sleep to an absolute number of hours, studies by Gruber et al. and Sadeh et al. asked participants to restrict or extend their sleep with respect to their typical sleep habits [12,13,50]. Of note, all studies employed objective measure of sleep: eight used only actigraphy [12,13,40–42,45,47,50], four used only polysomnography [43,44,48,49], and one used both forms of objective measures [46]. While the sleep restriction protocol mostly occurred in the child's natural home environment [12,13,40–42,45–47,49,50], a minority took place in a sleep lab and summer camps [43,44,48]. Please see Table 1 for a description of all sleep restriction protocols.

In sum, all sleep restriction protocols included a baseline period of typical sleep patterns. Within-subjects design studies employed a protocol in which participants were exposed to sleep restriction only or sleep restriction and sleep extension, in a counterbalanced fashion. Between-subjects design studies randomly assigned participants to either the sleep restriction condition or another condition (i.e. sleep extension or sleep as usual). The number of hours by which sleep was restricted, for how many nights and whether it was a function of their typical sleep patterns differed across studies. Most protocols took place in the comfort of the child's home.

10. Neurobehavioral assessment

There were several outcome measures used to assess NBF in the reviewed studies (see Table 1). Seven studies employed neurobehavioural tests such as the continuous performance task [12,13,50], digit symbol substitution test [49], n-back attentional task [40] and tests for listening attention [43,44]. Other studies included questionnaires that the teacher or parent completed pertaining to the NBF of the child before and after sleep restriction. One study assessed the effects of sleep restriction on NBF by observing how often the participants looked away from the film for 3 seconds or longer [42]. Another study used a simulation environment to assess attention to academic situations under sleep deprived and sleep as usual conditions [45]. In addition to the type of the NBF assessment used, the domains of NBF assessed differed between studies. For the most part, the domain of NBF [12,41,42,46,47]. Other domains of NBF assessed were arousal [49], sustained attention [8,43–45,48,50], divided attention and flexibility [48], working memory and fluid intelligence [40] and emotional lability [33]. In studies that assessed sustained attention, it was found that sleep restriction enhanced reaction time thus worsening performance on the NBF task [13,40,50]. For example, studies employing the Continuous Performance Test [13,50], a NBF task in which participants were instructed to respond to all signals except the target signal, consistently found that sleep restriction leads to increased reaction time (i.e. worse performance on the test). The studies assessing *inattentive or impulsive behaviour* according to teacher reports showed mixed results [12,46]. While the study utilizing the Conners' Global Index-Teacher version found that sleep restriction leads to increased impulsivity [12], the study that employed the Academic Situation, an observational assessment during 20 minutes academic exercise, found no association between sleep restriction and over-reactivity [46]. The one study assessing emotional lability found that sleep restriction significantly enhanced emotional lability as measured by the Conners' Global Index-Teacher version [12]. All studies assessing attention with a psychometric questionnaire found that sleep restriction worsened attention as reported by the teacher [46,47] and/or parent [41]. The results from studies using NBF tasks to measure attention are mixed with regards to the impact of sleep restriction on task performance. While the study that assessed performance on Digit Symbol Substitution found that sleep restriction reduced performance [49], studies involving a listening attention tasks and the n-back attentional task found that attention was not negatively affected by sleep restriction [40]. In studies whereby attention was assessed by teacher observation, result consistently showed that the attentional abilities of students decreased following sleep restriction [46,47].

Table 1
Studies evaluating the effect of sleep restriction on the NBF of normally developing children and adolescents.

Authors	Age range (years)	Design	Sample size	Females/ males	Sleep restriction protocol	Sleep measure(s)	Location of sleep monitoring	Objective measure of sleep (Y = yes, N = No)	Main outcomes related to attention	Findings
Inattentive or impulsive behavior										
Fallone et al., 2005 [47]	6–12	Within-subject cross-over design	74	35/39	Week 1: baseline week (self-selected school-night sleep schedule) Week 2 and 3 (counterbalanced): the restricted schedule week (If in grade 1 or 2, time in bed was restricted to 8 hours per night; if in grade 3 or above, time in bed was restricted to 6.5 hours per night) and the optimized schedule week (participants were in bed for at least 10 hours per night)	Actigraphy and sleep diary	Home	Y	Teachers observed the participant and completed the School Situations Questionnaire, which assesses the extent to which the participant pays attention in 8 school activities. The total number of problem settings and severity of the problems were assessed	Total number of problem settings was higher in both experimental weeks as compared to the baseline week (Restricted week: $F(1,69) = 9.24$; $P < .01$; Optimized week: $F(1,69) = 6.44$, $P < .02$). However, there were no significant differences between the two experimental weeks. Further, the mean severity of the problems were higher in the restricted week as compared to the baseline week ($F(1,69) = 9.39$, $P < .01$) but not the optimized week
Fallone et al., 2001 [46]	6–15	Between-subject design	82	39/43	Day 1–5: baseline sleep schedule (minimum sleep duration was 10 hours per night) Day 6: optimized sleep (21:00–07:00) or restricted sleep condition (0300–0700)	Actigraphy, polymonagraphy and sleep diary	Home and sleep lab	Y	The Child Attention Profile: behavior rating scale including 7 inattentive behaviours The Restricted Academic Situation: children were observed during a 20-minute academic exercise and rated on overactive and inattentive behaviours	Child Attention Profile: participants in the restricted sleep condition as compared to participants in the optimized sleep condition were rated as more inattentive according to the child attention profile ($P < .10$) The Restricted Academic Situation: there were no differences in inattentiveness and over-reactivity in participants in the restricted sleep condition and the optimized sleep condition

Table 1 (*Continued*)

Authors	Age range (years)	Design	Sample size	Females/ males	Sleep restriction protocol	Sleep measure(s)	Location of sleep monitoring	Objective measure of sleep (Y = yes, N = No)	Main outcomes related to attention	Findings
Gruber et al., 2012 [12]	7–11	Between-subject design	34	14/20	Participants were assigned to either the sleep restriction or sleep extension condition Sleep extension condition: addition of 1 hour relative to typical night time sleep Sleep restriction condition: reduction of 1 hour relative to typical night time sleep	Actigraphy	Home	Y	The emotional lability and restless-impulsive behaviour subscales of the Conners' Global Index-Teacher	A significant interaction was found when CGI-T measures were examined ($F(3,30) = 3.75$, $P < .05$, b = .76). Emotional lability and restless-impulsivity scores improved significantly from baseline in children in the sleep extension group, whereas Emotional lability and restless-impulsivity scores deteriorated in children experiencing sleep restriction
Beebe et al., 2008 [41]	13.9–16.9	Within-subject cross-over design	20	8/12	Week 1: self-selected schedule (no sleep restrictions) Week 2 and Week 3 (counterbalanced): the sleep-restricted week (restrict time in bed to 6.5 hours) and the extended sleep week (extend time in bed to 10 hours)	Sleep diary (bedtime, sleep latency, rise time and napping) and actigraphy during weekdays	Home	Y	Parental responses on the inattention subscale of the Vanderbuilt Assessment Scale	Parents reported increased inattention in the sleep-restricted week as compared to the extended sleep week ($t > 3.3$, $P < .002$)
Beebe et al., 2010 [42]	14.5–16.1	Within-subject cross-over design	8	5/3	Same protocol as Beebe et al., 2008	Same sleep measures as Beebe et al., 2008	Home	Y	Participants were videotaped while experiencing a simulated classroom (watching educational films). Inattentiveness was measured as a function of the number of times in which the participant looked away from the film for 3 seconds or longer	In the restricted sleep condition, participants displayed more inattentive behaviours ($t(7) = 2.6$, $P < .05$, d = .98)
Arousal										
Randazzo et al., 1998 [49]	10–14	Between-subject design	16S	9/7	Participants were randomly assigned to the sleep-restricted group (5 hours in bed between 03:00 and 08:00) or the control group (allowed 11 hours in bed between 21:00 and 08:00)	Polysomnography	Home and sleep lab	Y	Participants completed the Digit Symbol Substitution Test (DSST) four times throughout the day, which involved first rehearsing a set of nine numbers with matching symbols and then writing the correct matching symbol under a series of numbers. The score is the number of correct matches	Performance on the DSST improved over time ($F(3,39) = 10.30$; $P < .001$), but there was no main effect of group ($F(1,13) = 1.315$, $P = 0.272$). However, there was a time-by-group interaction such that although both groups improved throughout the day at the DSST, the sleep-restricted group improved significantly less than the control group ($F(3,39) = 3.778$; $P = 018$)

Table 1 (*Continued*)

Authors	Age range (years)	Design	Sample size	Females/ males	Sleep restriction protocol	Sleep measure(s)	Location of sleep monitoring	Objective measure of sleep (Y = yes, N = No)	Main outcomes related to attention	Findings
Sustained attention										
Gruber et al., 2011 [13]	7–11	Within-subject design	32 (control participants only)	12/20	Day 1–6: baseline week (self-selected schedule) Day 7–12: sleep restriction week (children were asked to go to bed 1 hour later than they usually do in order to decrease their sleep duration by 1 hour)	Actigraphy and sleep diary	Home	Y	Participants completed the Continuous Performance Test (CPT) after baseline and sleep restriction weeks. During the task, letters appear on a screen at different rates (once every second, once every two seconds or once every four seconds) and participants are instructed to press a button in response to all signals except the target signal. Average reaction time, reaction time variability, reaction time change by inter-stimulus interval (ISI), signal detectability, omission and commission errors were measured to assess attention	As compared to the baseline week, participants exhibited a slower reaction time ($F(1,41) = 16.58$, $P < 0.001$), a higher variability in ISIs ($F(1,41) = 7.38$, $P = 0.01$), a change in RT on the ISIs ($F(1,41) = 7.02$, $P = 0.01$), change in detectability ($F(1,41) = 4.15$, $P < 0.05$), greater number of omission errors ($F(1,41) = 8.68$, $P = 0.005$) and a lower number of commission errors ($F(1,41) = 11.37$, $P = 0.002$) following the sleep restriction week
Sadeh et al., 2003 [50]	9.1–12.2	Between-subject design	77	38/39	Day 1–2: baseline (sleep as usual) Day 3–6: participants were randomly assigned to the sleep-restricted condition (participants were told to go to sleep 1 hour later than usual) or the sleep extension condition (participants were told to go to sleep 1 hour earlier than usual)	Actigraphy and sleep diaries	Home	Y	Participants completed the CPT where they were told to respond as quickly as possible to a specific animal and avoid responding to another animal. Average reaction time, omission and commission errors were measured to assess sustained visual attention. Participants also completed the visual digit span test in which they repeatedly typed number sequences on the computer keyboard in forward and backward direction. The length of the longest sequence answered correctly forward and backward was measured to assess attention	Children in the sleep extension group displayed significant improvements in the visual digit span test (forward direction; $F(2,61) = 6.74$; $P < 0.005$) and the CPT (lower reaction time; $F(2,61) = 3.25$; $P < 0.05$) as compared to the sleep-restricted group. The other attentional variables assessed were not significantly different between groups
Carskadon et al., 1981 [43]	11–13.2	Within-subject design	9	6/3	Day 1: baseline (bedtime at 10PM and rise time at 8AM) Day 2: restricted sleep (bedtime at 4AM and rise time at 8AM) Day 3: recovery day (same as baseline)	Polysomnography	Summer sleep camp	Y	Participants listened to a 10-minute passage and were instructed to press a switch when hearing two key words. Inattention was measured by the total number of key words missed on each tape	There were no significant differences between performance on the listening attention task on sleep-restricted and baseline/recovery days

Table 1 (*Continued*)

Authors	Age range (years)	Design	Sample size	Females/ males	Sleep restriction protocol	Sleep measure(s)	Location of sleep monitoring	Objective measure of sleep (Y = yes, N = No)	Main outcomes related to attention	Findings
Carskadon et al., 1981 [44]	11.7–14.6	Within-subject design	12	4/8	Day 1: adaptation day (subjects were in bed for 10 hours at night) Day 2–3: baseline days (same as adaptation day) Day 4: sleep deprivation day Day 5–6: recovery days (same as adaptation night)	Polysomnography	Summer sleep camp	Y	Same listening attention task as Carskadon et al., 1981	There were no significant differences between performance on the listening attention tasks on sleep deprivation and baseline/recovery sleep days
Davis et al., 2013 [45]	14–15	Within-subject cross-over design	55	32/23	After a week of the baseline visit, half participants underwent sleep restriction of 4 hours less than usual bedtime a night before experiment, the other half presented with normal sleep. The condition was reversed in subsequent visit usually within two weeks of the baseline visit	Actigraphy, sleep diary	Home	Y	Participants underwent 25 trials of pedestrian crossings with two outcomes related to attention: (1) hits or close calls of 25 crossings; (2) attention to traffic (looked right and left before crossing divided by wait time)	Significant differences were observed for outcomes 1 and 2: Cohen's *d* for hits and closed calls was 0.32 and for attention to traffic was 0.31 ($P < 0.05$)
Kopasz et al., 2010 [48]	14–16	Within-subject cross-over design	22	12/10	The order of conditions was counterbalanced across participants Experimental condition Day 1: adaptation night (9 hours of sleep) baseline Day 2: partial sleep deprivation (4 hours of sleep) Day 3: recovery night (9 hours of sleep) Control condition Day 1: adaptation night (9 hours of sleep) Day 2: control night (9 hours of sleep) Day 3: second control night (9 hours of sleep)	Polysomnography	Sleep lab	Y	Participants completed the Test for Attention Performance (TAP) that assesses divided attention and flexibility and the d2 test that assesses sustained attention and concentration	There were no significant differences in performance on the TAP (divided attention: $P = 0.322$; flexibility: $P = 0.884$; and d2 $P = 0.135$) tasks between the control and experimental condition

Table 1 (*Continued*)

Authors	Age range (years)	Design	Sample size	Females/ males	Sleep restriction protocol	Sleep measure(s)	Location of sleep monitoring	Objective measure of sleep (Y = yes, N = No)	Main outcomes related to attention	Findings
Divided attention and flexibility										
Kopasz et al., 2010 [48]	14–16	Within-subject cross-over design	22	12/10	The order of conditions was counterbalanced across participants Experimental condition Day 1: adaptation night (9 hours of sleep) baseline Day 2: partial sleep deprivation (4 hours of sleep) Day 3: recovery night (9 hours of sleep) Control condition Day 1: adaptation night (9 hours of sleep) Day 2: control night (9 hours of sleep) Day 3: second control night (9 hours of sleep)	Polysomnography	Sleep lab	Y	Participants completed the Test for Attention Performance (TAP) that assesses divided attention and flexibility and the d2 test that assesses sustained attention and concentration	There were no significant differences in performance on the TAP (divided attention: $P = 0.322$; flexibility: $P = 0.884$; and d2 $P = 0.135$) tasks between the control and experimental condition
Working memory and fluid intelligence										
Beebe et al., 2009 [40]	14.6–16	Within-subject cross-over design	6	2/4	Same protocol as Beebe et al., 2008	Same sleep measures as Beebe et al., 2008	Home	Y	Accuracy and reaction time on the n-back attentional task	There was no significant difference between both conditions in performance on the n-back task ($P > .10$)

Table 1 (*Continued*)

Authors	Age range (years)	Design	Sample size	Females/ males	Sleep restriction protocol	Sleep measure(s)	Location of sleep monitoring	Objective measure of sleep (Y = yes, N = No)	Main outcomes related to attention	Findings
Emotional lability										
Gruber et al., 2012 [12]	7–11	Between-subject design	34	14/20	Participants were assigned to either the sleep restriction or sleep extension condition Sleep extension condition: addition of 1 hour relative to typical night time sleep Sleep restriction condition: reduction of 1 hour relative to typical night time sleep	Actigraphy	Home	Y	The emotional lability and restless-impulsive behaviour subscales of the Conners' Global Index-Teacher	A significant interaction was found when CGI-T measures were examined ($F(3,30) = 3.75$, $P < .05$, b = .76). Emotional lability and restless-impulsivity scores improved significantly from baseline in children in the sleep extension group, whereas Emotional lability and restless-impulsivity scores deteriorated in children experiencing sleep restriction

The table is organized according to domain of NBF assessed in each study. Within each section, the table is further sorted according to age of participants, starting with the youngest range of participants. Gruber et al., 2012 [12] is listed in the table twice as the study assesses emotional lability and impulsive behavior. Kopasz et al., 2010 [48] is also listed twice as the study assessed sustained attention as well as divided attention and flexibility.

11. Discussion

Findings amongst the reviewed studies are inconsistent with regards to the effects of sleep restriction on NBF outcomes in that the majority of studies found that sleep restriction causes impairments in NBF [12,13,41,42,45,47,49,50] while others [40,43,44,46,48] found that NBF is not significantly affected by lack of sleep. The inconsistency of findings can be attributed to noteworthy differences amongst studies. First, the outcome measures used to assess attention varied across studies. While attention constructs assessed by psychometric questionnaires (e.g., Vanderbuilt Assessment Scale [41], The Child Attention Profile [46]) declined following sleep restriction, attention outcomes assessed with neurobehavioral tasks (e.g. N-back Attentional Task, Test for Attention Performance) showed mixed results. Using consistent NBF assessments tools across studies that are reliable and sensitive to small changes in NBF is necessary to clarify whether sleep restriction can significantly impact the NBF of normally developing pediatric populations. The ABS lab is working to address this gap by using complex phenotyping including neurobehavioral tools that allow to measure NBF changes in a sensitive and reliable manner, while minimizing self-report bias.

A factor that might have contributed to the inconsistency of the findings is the extent to which the participants were sleep-restricted. In studies where sleep restriction was for only one night [43,44,48], the sleep deficit had less of a detrimental impact on attention than in studies where adolescents were sleep deprived for an entire week [42,47]. It may be the case that the inconsistencies in which participants were sleep-restricted can significantly impact performance on neurobehavioral attentional tasks. In order to ensure that participants are sleep-restricted in a similar manner, the ABS lab and other research teams are implementing sleep restriction protocols that restrict sleep relative to typical schedules rather than enforcing set bedtimes and wake times. Forcing the participant to go to sleep at a certain time can result in some participants not experiencing sleep restriction if their typical bedtime is similar to the prescribed regimen of the sleep restriction protocol. Given that participants will typically demonstrate very different sleep schedules, a sleep restriction paradigm allowing bedtime and wake time to vary depending on the schedule of the individual sleep schedules will ensure that each participant is experiencing the same extent of sleep restriction.

Another factor that may have contributed to the inconsistency in findings is the low statistical power of the reviewed studies [38]. Several studies reported a sample size of under 20 participants [40,43,44] and therefore it may be the case that with an increased sample size resulting in sufficient power, statistical significance would be reached. According to the Down and Black criteria, only 1 of the reviewed studies had ample power. Of note, sleep restriction protocols are very demanding in terms of time and cost and therefore large sample sizes are difficult to obtain. Conducting sleep assessments in the child's home instead of the lab is less time and financially burdensome and may facilitate increasing sample size in sleep restriction studies [22,51].

Given the inconsistency in outcome measures, experimental protocols and statistical power, the studies reviewed herein remain difficult to interpret. Despite mixed findings, the majority of studies do show sleep restriction can cause deficits in the NBF of children and adolescents [12,13,41,42,45,47,49,50]. Strategies used by the ABS including implementing home assessments of sleep, restricting sleep relative to the participants' typical sleepschedules, blinding raters who assess NBF, and using valid and reliable NBF assessments [12,13,50] are an attempt to address the gaps in this research area and clarify the causal relationship between sleep restriction and NBF in typically developing children and adolescents.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

References

[1] Curcio G, Ferrara M, De Gennaro L. Sleep loss, learning capacity and academic performance. Sleep Med Rev 2006;10(5):323–37.

[2] Astill RG, Van der Heijden KB, Van IJzendoorn MH, Van Someren EJ. Sleep, cognition, and behavioral problems in school-age children: a century of research meta-analyzed. Psychol Bull 2012;138(6):1109.

[3] Hart CN, Cairns A, Jelalian E. Sleep and obesity in children and adolescents. Pediatr Clin North Am 2011;58(3):715.

[4] Gruber R, Wiebe ST, Wells S, Cassoff J, Monson E. Sleep and academic success: mechanisms, empirical evidence, and interventional strategies. Adolesc Med 2010;21(3):522–41 [x].

[5] Matricciani L, Olds T, Petkov J. In search of lost sleep: secular trends in the sleep time of school-aged children and adolescents. Sleep Med Rev 2012;16(3):203–11.

[6] Iglowstein I, Jenni OG, Molinari L, Largo RH. Sleep duration from infancy to adolescence: reference values and generational trends. Pediatrics 2003;111(2):302–7.

[7] Shochat T, Cohen-Zion M, Tzischinsky O. Functional consequences of inadequate sleep in adolescents: a systematic review. Sleep Med Rev 2014;18(1):75–87.

[8] Gruber R, Cassoff J, Knäuper B. Sleep health education in pediatric community settings: rationale and practical suggestions for incorporating healthy sleep education into pediatric practice. Pediatr Clin North Am 2011;58:735–54.

[9] Association AP. Diagnostic and statistical manual of mental disorders: DSM-IV-TR®. American Psychiatric Pub; 2000.

[10] Polanczyk G, de Lima M, Horta B, Biederman J, Rohde L. The worldwide prevalence of ADHD: a systematic review and metaregression analysis. Am J Psychiatry 2007;164(6):942–8.

[11] Corkum P, Tannock R, Moldofsky H. Sleep disturbances in children with attention deficit/hyperactivity disorder. J Am Acad Child Adolesc Psychiatry 1998;37(6):637–46.

[12] Gruber R, Cassoff J, Frenette S, Wiebe S, Carrier J. Impact of sleep extension and restriction on children's emotional lability and impulsivity. Pediatrics 2012;130(5):e1155–61.

[13] Gruber R, Wiebe S, Montecalvo L, Brunetti B, Amsel R, Carrier J. Impact of sleep restriction on neurobehavioral functioning of children with attention deficit hyperactivity disorder. Sleep 2011;34(3):315–23.

[14] Gruber R, Wise MS, Frenette S, Knäauper B, Boom A, Fontil L, et al. The association between sleep spindles and IQ in healthy school-age children. Int J Psychophysiol 2013;89(2):229–40.

[15] Gruber R, Xi T, Frenette S, Robert M, Vannasinh P, Carrier J. Sleep disturbances in prepubertal children with attention deficit hyperactivity disorder: a home polysomnography study. Sleep 2009;32(3):343–50.

[16] Lobstein T, Baur L, Uauy R. Obesity in children and young people: a crisis in public health. Obes Rev 2004;5(s1):4–85.

[17] Hart CN, Carskadon MA, Considine RV, Fava JL, Lawton J, Raynor HA, et al. Changes in children's sleep duration on food intake, weight, and leptin. Pediatrics 2013;132(6):e1473–80.

[18] Taheri S, Lin L, Austin D, Young T, Mignot E. Short sleep duration is associated with reduced leptin, elevated ghrelin, and increased body mass index. PLoS Med 2004;1(3):e62.

[19] Yaggi HK, Araujo AB, McKinlay JB. Sleep duration as a risk factor for the development of type 2 diabetes. Diabetes Care 2006;29(3):657–61.

[20] Vgontzas AN, Liao D, Bixler EO, Chrousos GP, Vela-Bueno A. Insomnia with objective short sleep duration is associated with a high risk for hypertension. Sleep 2009;32(4):491.

[21] Maayan L, Hoogendoorn C, Sweat V, Convit A. Disinhibited eating in obese adolescents is associated with orbitofrontal volume reductions and executive dysfunction. Obesity 2011;19(7):1382–7.

[22] Gruber R, Laviolette R, Deluca P, Monson E, Cornish K, Carrier J. Short sleep duration is associated with poor performance on IQ measures in healthy school-age children. Sleep Med 2010;11(3):289–94.

[23] Dewald JF, Meijer AM, Oort FJ, Kerkhof GA, Bögels SM. The influence of sleep quality, sleep duration and sleepiness on school performance in children and adolescents: a meta-analytic review. Sleep Med Rev 2010;14(3):179–89.

[24] Sadeh A, Gruber R, Raviv A. Sleep, neurobehavioral functioning, and behavior problems in school-age children. Child Dev 2002;73(2):405–17.

[25] Sadeh A, Gruber R, Raviv A. The effects of sleep restriction/extension on school-age children: what a difference an hour makes? Child Dev 2003;74:444–55.

[26] Touchette É, Petit D, Séguin JR, Boivin M, Tremblay RE, Montplaisir JY. Associations between sleep duration patterns and behavioral/cognitive functioning at school entry. Sleep 2007;30(9):1213–9.

[27] Dinges DF, Pack F, Williams K, Gillen KA, Powell JW, Ott GE, et al. Cumulative sleepiness, mood disturbance, and psychomotor vigilance performance decrements during a week of sleep-restricted to 4–5 h per night. Sleep 1997;20(4):267–77.

[28] Gibson ES, Powles ACP, Chilcott L, Carll D, O'Brien S, Ogilvie R, et al. The impact of "sleepiness" on adolescent students. Report of Population Health Grant 5555-15-1997-0000051. Canada: Health Canada; 1998–2002.

[29] Wolfson AR, Carskadon MA. Sleep schedules and daytime functioning in adolescents. Child Dev 1998;69:875–87.
[30] Beebe DW. Cognitive, behavioral, and functional consequences of inadequate sleep in children and adolescents. Pediatr Clin North Am 2011;58(3):649.
[31] Dahl RE, Lewin DS. Pathways to adolescent health sleep regulation and behavior. J Adolesc Health 2002;31(6):175–84.
[32] Lufi D, Tzischinsky O, Hadar S. Delaying school starting time by one hour: some effects on attention levels in adolescents. J Clin Sleep Med 2011;7(2):137.
[33] Gruber R, Michaelsen S, Bergmame L, Frenette S, Bruni O, Fontil L, et al. Short sleep duration is associated with teacher-reported inattention and cognitive problems in healthy school-aged children. Nat Sci Sleep 2012;4:33.
[34] Gruber R, EGillies-Poitras E, Enros P, Kestler M, Lessard I, Bergmame L, et al. Sleep for success: the impact of school-based program on the sleep and the day time functioning of school-age children. J Sleep Sleep Disorders Res 2012;35:A365.
[35] Ioannidis J. Materializing research promises: opportunities, priorities and conflicts in translational medicine. J Transl Med 2004;2(1):5.
[36] Maski KP, Kothare SV. Sleep deprivation and neurobehavioral functioning in children. Int J Psychophysiol 2013.
[37] National Sleep Foundation. Sleep in America Poll 2004. Washington, DC: National Sleep Foundation; 2004.
[38] Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. J Epidemiol Community Health 1998;52(6):377–84.
[39] Gaynes BN, Gavin N, Meltzer-Brody S, Lohr KN, Swinson T, Gartlehner G, et al. Perinatal depression: prevalence, screening accuracy, and screening outcomes: summary, evidence report/technology assessment No. 119. Rockville, MD: Agency for Healthcare Research and Quality; 2005.
[40] Beebe DW, Di Francesco MW, Tlustos SJ, McNally KA, Holland SK. Preliminary fMRI findings in experimentally sleep-restricted adolescents engaged in a working memory task. Behav Brain Funct 2009;5:9.
[41] Beebe DW, Fallone G, Godiwala N, Flanigan M, Martin D, Schaffner L, et al. Feasibility and behavioral effects of an at home multi-night sleep restriction protocol for adolescents. J Child Psychol Psychiatry 2008;49(9):915–23.
[42] Beebe DW, Rose D, Amin R. Attention, learning, and arousal of experimentally sleep-restricted adolescents in a simulated classroom. J Adolesc Health 2010;47(5):523–5.
[43] Carskadon MA, Harvey K, Dement WC. Acute restriction of nocturnal sleep in children. Percept Mot Skills 1981;53(1):103–12.
[44] Carskadon MA, Harvey K, Dement WC. Sleep loss in young adolescents. Sleep 1981;4(3):299–312.
[45] Davis AL, Avis KT, Schwebel DC. The effects of acute sleep restriction on adolescents' pedestrian safety in a virtual environment. J Adolesc Health 2013;53(6):785–90.
[46] Fallone G, Acebo C, Arnedt J, Seifer R, Carskadon MA. Effects of acute sleep restriction on behavior, sustained attention, and response inhibition in children. Percept Mot Skills 2001;93(1):213–29.
[47] Fallone G, Acebo C, Seifer R, Carskadon MA. Experimental restriction of sleep opportunity in children: effects on teacher ratings. Sleep 2005;28(12):1561–7.
[48] Kopasz M, Loessl B, Valerius G, Koenig E, Matthaeas N, Hornyak M, et al. No persisting effect of partial sleep curtailment on cognitive performance and declarative memory recall in adolescents. J Sleep Res 2010;19(1 Part 1):71–9.
[49] Randazzo AC, Muehlbach MJ, Schweitzer PK, Walsh JK. Cognitive function following acute sleep restriction in children ages 10–14. Sleep 1998;21(8):861–8.
[50] Sadeh A, Gruber R, Raviv A. The effects of sleep restriction and extension on school-age children: what a difference an hour makes. Child Dev 2003;74(2):444–55.
[51] Amorim A, Sucena M, Winck JC, Almeida J. [Home cardiorespiratory sleep study in children. Will it be feasible?] Rev Port Pneumol 2004;10(6):463–74.